

On the relative Contribution of high-redshift Galaxies and Active Galactic Nuclei to Reionization.

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ABSTRACT

In this paper we discuss the contribution of different astrophysical sources to the ionization of neutral hydrogen at different redshifts. We critically revise the arguments in favour/against a substantial contribution of Active Galactic Nuclei (AGNs) and/or Lyman Break Galaxies (LBGs) to the reionization of the Universe at $z > 5$. We consider extrapolations of the high- z QSO and LBG luminosity functions and their redshift evolution as well as indirect constraints on the space density of lower luminosity Active Galactic Nuclei based on the galaxy stellar mass function. Since the hypothesis of a reionization due to LBGs alone requires a significant contribution of faint dwarf galaxies and a LyC photon escape fraction (f_{esc}) of the order of $\sim 20\%$, in tension with present observational constraints, we examine under which hypothesis AGNs and LBGs may provide a combined relevant contribution to the reionization. We show that a relatively steep faint-end of the AGN luminosity function, consistent with present constraints, provides a relevant (although sub-dominant) contribution, thus allowing us to recover the required ionizing photon rates with $f_{\text{esc}} \sim 5\%$ up to $z \sim 7$. At higher redshifts, we test the case for a luminosity-dependent f_{esc} scenario and we conclude that, if the observed LBGs are indeed characterized by very low f_{esc} , values of the order of $f_{\text{esc}} \sim 70\%$ are needed for objects below our detection threshold, for this galaxy population to provide a substantial contribution to reionization. Clearly, the study of the properties of faint sources (both AGNs and LBGs) is crucial.

Key words: cosmology: observation - early Universe - quasars: general - galaxies: active - galaxies: evolution

1 INTRODUCTION

Cosmic reionization is a major focus in present Cosmology, since it represents a crucial cosmic epoch for the formation of the first structures and the production of the photons responsible for the end the Dark post-recombination Ages. Moreover, these energetic photons affect, in a critical interplay, the species available for gas cooling (and consequently the star formation) and the collapse of (small) dark matter halos.

An important constraint on the epoch when this phase transition occurs is set by the measurement of the Thomson optical depth of the intergalactic medium (IGM) via the large scale polarization of the Cosmic Microwave Background (CMB, Komatsu et al. 2011), which provides - with the rough assumption of instantaneous reionization - $\tau_{\text{reion}} = 10.6 \pm 1.2$. Additional evidence comes from the Gunn-Peterson test applied at the Lyman- α forest, characterized by a low neutral hydrogen fraction at redshifts below 6 (Fan et al. 2006, but see also McGreer et al. 2011). Recent evidence for a damping wing around the systemic redshift of

a $z=7.085$ quasar (Bolton et al. 2011) and for a sudden decrease in the fraction of Lyman- α emitters among $z \sim 7$ Lyman-break galaxies (LBG, see e.g., Pentericci et al. 2011; Schenker et al. 2012; Ono et al. 2012) also suggests a rapid increase of the neutral fraction of hydrogen in the Universe at these epochs. All these evidences broadly constrain the epoch of hydrogen reionization in the redshift range $6 < z < 12$.

At the same time, many studies have addressed the nature of the ionizing sources. Pop III stars (e.g. Ciardi et al. 2000), star-forming galaxies (e.g. Robertson et al. 2010), and Active Galactic Nuclei (AGNs, e.g. Haiman & Loeb 1998) have found to be prime candidates, with more exotic possibilities explored in the form of primordial black-holes and mini-quasars (e.g. Madau et al. 2004), and decaying particles (dark matter and neutrinos, e.g. Scott et al. 1991; Pierpaoli 2004). It is commonplace that by $z \sim 6$ the ionizing radiation emitted by quasars alone is insufficient to reionize the IGM (e.g. Schirber & Bullock 2003; Cowie et al. 2009); on the other hand high-redshift galaxies are in principle able to produce the bulk of the cosmic emissivity ionizing the IGM (see

Haardt & Madau (2012) for a recent analysis), but only if the fraction of the 1-4 Ryd photons escaping the galaxies is significant ($\sim 20\%$ at $z \simeq 7$, see also Bouwens et al. 2011) and if the contribution of very faint, undetected objects is taken into account, assuming their space density is satisfactorily described by the extrapolation of the faint-end of observed luminosity function (LF). Nonetheless, the direct detection of Lyman continuum (LyC) photons from low redshift ($z < 1.5$) galaxies has been so far unsuccessful (Cowie et al. 2009; Siana et al. 2010), down to $f_{\text{esc}} < 1\%$, and the measurements at the highest redshifts for which the direct LyC measurement is still allowed by the rapidly increasing IGM opacity ($z = 3-4$) have been shown to be prone to a significant degree of contamination by lower-redshift interlopers (Vanzella et al. 2010a, 2012).

The results of numerical hydrodynamical simulations (see e.g. Ciardi et al. 2011) also favour sources with a soft spectral energy distribution (indicative of Population II stars) and high escape fractions as the main contributors to Hydrogen reionization. On the other hand, numerical simulations have not provided yet a concordant answer to the question of f_{esc} evolution as a function of galaxy properties, luminosities and redshift: some groups reported evidence for a *decrease* of f_{esc} with decreasing halo mass at $z > 3$ (e.g. Gnedin et al. 2008), while competing groups have found the exactly opposite result of an *increase* of f_{esc} with decreasing halo mass (e.g. Yajima et al. 2011, with a large scatter in the individual f_{esc} determinations).

The magnitude of the faintest dwarf galaxies represents another critical point in the analysis. The expected absolute magnitude at 145 nm (M_{UV}) of a galaxy hosted in a halo with virial temperature $\sim 2 \times 10^4 K$ is $M_{\text{UV}} \sim -10$ (see e.g. Trenti et al. 2010). However, theoretical models also suggest that star formation might be strongly suppressed in early $M_{\text{UV}} \gtrsim -13$ dwarfs due to metallicity effects (Krumholz & Dekel 2011; Kuhlen et al. 2012). Moreover, if faint galaxies were the major contributors to reionization, this would imply an extended reionization epoch, a result disfavoured by recent constraints on kinetic Sunyaev-Zel'dovich effect (Zahn et al. 2011; Kuhlen & Faucher-Giguere 2012). Therefore, if these dwarfs would not be able to provide the required contribution to the ionizing background, additional assumptions have to be tested, as a strong luminosity/redshift evolution of f_{esc} or the inclusion additional sources of ionizing photons.

All these considerations point out the need of a deeper investigation of the (possibly sub-dominant) contribution of AGNs to the ionizing flux, in order to explore to which extent these sources may be able to alleviate the tensions arising from considering galaxies as the only contributors to cosmic reionization. In this paper, we thus revisit and compare the relative contribution of AGNs and galaxies to the ionizing background at $z > 5$. In particular, we focus on the putative role played by faint AGNs, up to the same magnitude limits considered for galaxies. Both the determination of the faint end of the observed AGN luminosity function and the reliability of its extrapolation to fainter magnitudes present similar challenges with respect to analogous statistical estimators for galaxies. An additional source of uncertainty, however, arises from the apparently discrepant results obtained using independent selection techniques for the reference sample, i.e. X-ray or optically based, which show a different sensitivity to the various AGN populations. Nonetheless, it is also possible to combine the most recent determination the galaxy stellar mass function of galaxies (Santini et al. 2012) with empirical arguments, to get an estimate of the maximum contribution of the AGN population to the cosmic reionization.

The structure of this paper is as follows: in sec. 2 we present

the formalism we adopt to estimate the contribution of each class of sources with respect to the required ionization photon rate; while in sec. 3 we discuss the implication of our finding and in sec. 4 we present our conclusions. Throughout this paper we assume that QSOs represent the luminous sub-population of the homogeneous AGN population, and that Lyman Break Galaxies are a good tracer of the overall galactic population.

2 MODELING THE CONTRIBUTION TO REIONIZATION OF DIFFERENT ASTROPHYSICAL SOURCES

2.1 High- z QSO/AGN Luminosity Functions

In order to estimate the contribution of quasars (QSOs) to the reionization we consider different observational constraints. A first set includes direct measurements of their high- z LF and its redshift evolution. In this class, we consider both the optical QSO-LF derived in the framework of the Great Observatories Origins Deep Survey (GOODS) collaboration by Fontanot et al. (2007, F07 hereafter) and the X-ray selected QSO-LF by Fiore et al. (2012). Moreover, we also consider the upped limit estimate from Shankar & Mathur (2007): they use the results of optical surveys down to the highest redshifts and faintest magnitudes proven (critically including non-detections) to give constraints on the faint end of the QSO-LF at $z > 5$. Their analysis shows that the observational constraints found so far are compatible with a faint-end slope of $\alpha = -2.8$ (at 99% confidence level) and $\alpha = -2.2$ (at 90% confidence level). We directly compare these three estimates in Fig. 1; X-ray measurements and the relative analytical fits have been converted into absolute magnitude M_{UV} by means of the QSO bolometric corrections proposed by Marconi et al. (2004); Elvis et al. (1994); Fontanot et al. (2007). The three estimates agree well at the bright-end of the LF; on the other hand the agreement is considerably reduced at the faint-end of the LF and at higher redshift due to the different redshift evolution extrapolated to higher redshift (Fontanot et al. 2007). This behaviour is in part related to the different selection of QSO databases: it is indeed quite clear that X-ray surveys observe higher faint QSO space densities than optical surveys. It is also worth stressing that we expect obscuration effects to play a relevant role at these luminosities (see e.g. Simpson 2005). Moreover, at these luminosities we are no longer considering only “bona fide” QSOs (i.e. $M_B < -23$), but we are entering a regime where the AGN/QSO distinction becomes loose.

If the QSO population and its high- z LF is representative only of a sub-population of the global AGN population, we may as well be missing a relevant contribution to the ionizing flux. As an alternative approach to gain insight into the AGN LF and in particular its faint end slope we consider the galaxy stellar mass function (GSMF) as estimated in the redshift range $0.4 < z < 4.5$ by Santini et al. (2012). Following simple empirical reasoning we tried to use the constraints provided by the Santini et al. (2012) analysis in their highest redshift bin ($3.5 < z < 4.5$). In particular we assume:

- (a) each galaxy host a Supermassive Black Hole (SMBH) at its center, and the relation between galaxy stellar mass and SMBH mass is the same as in local Universe (Magorrian et al. 1998; Häring & Rix 2004, i.e. all galaxies are ellipticals);
- (b) the estimated faint end of the GSMF is a good representation of the dwarf population;
- (c) the high- z QSO-LF is a rescaled version of the GSMF;

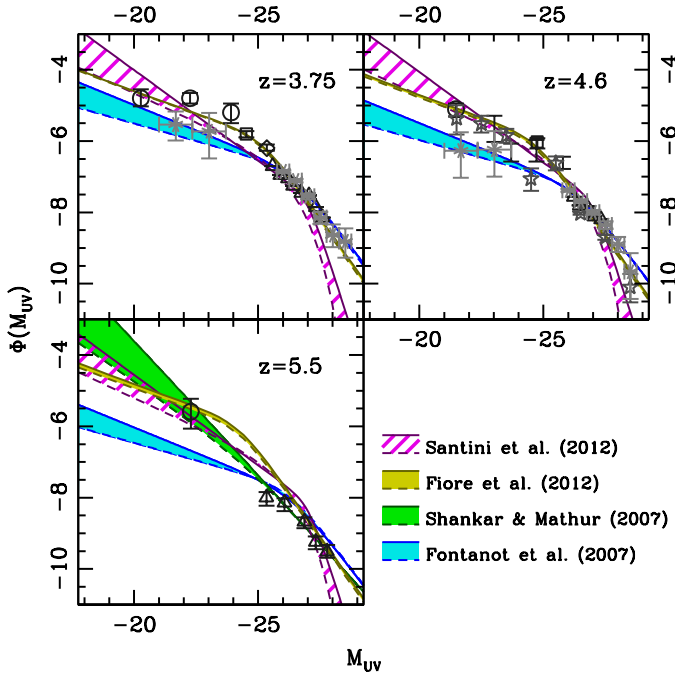


Figure 1. Comparison of different estimates for the high- z QSO-LF. Blue lines and light blue shaded region correspond to the best fit models in Fontanot et al. (2007), and their redshift evolution. Green lines and light green shading correspond to the models in Shankar & Mathur (2007). Yellow line corresponds to the evolution of X-ray selected QSO-LF in Fiore et al. (2012). Red lines and hatched light red shading correspond to the GSMF-derived high- z AGN-LF (see text for more details on the conversion from GSMF to QSO-LF). Dots refer to datapoints from Fontanot et al. (2007, grey asterisks), Fiore et al. (2012, open circles), Civano et al. (2011, open squares), Brusa et al. (2010, open diamonds), Glikman et al. (2011, stars), Jiang et al. (2009, open triangles).

(d) at $z > 4.5$ the GSMF evolves as the F07 QSO-LF: i.e. an exponential pure density evolution proportional to $e^{-1.26(1+z)}$;

(e) at each redshift only 0.45% of SMBH shine at their Eddington luminosity (see e.g. Haiman et al. 2004);

(f) conversion from bolometric luminosity to M_{UV} using a standard approach (see e.g., F07): we consider a bolometric correction factor for the B -band luminosity of 10.4 (Elvis et al. 1994) and a B - to UV -magnitude shift of -0.48 mag.

We show the result of these conversions in Fig. 1: the red lines (and hatched light red shading in between) correspond to the upper and lower best-fits¹ in Santini et al. (2012) in the range $3.5 < z < 4.5$. It is interesting to stress that the knee of the “mass-derived” luminosity function results in a good agreement with respect to F07 best-fit models, and the overall normalization is consistent with the densities obtained in QSO-LF studies. This is an important sanity check for the proposed approach, since some of the factors (a) to (f) are degenerate and uncertain as well. In particular, there are several evidences in favour of a redshift evolution of both the ratio

¹ In particular, the upper envelope corresponds to the best fit to a double power yielding a normalization $\log(\Phi_*) = -4.84$, a characteristic mass $\log(M_*) = 11.81$, an high-mass-end slope $\beta = -6.38$ and a low-mass-end slope $\alpha = -2.27$ (table 3 in Santini et al. 2012); while the lower envelope refers to the best-fit to a Schechter function yielding $\log(\Phi_*) = -4.12$, $\log(M_*) = 11.30$ and $\alpha = -1.80$ (table 1 in Santini et al. 2012).

between SMBH mass and the spheroidal host component mass, and on the AGN fraction/duty cycle (see e.g. Shankar 2009; Fiore et al. 2012 and discussion herein). The bright-end of the AGN-LF is steeper than any QSO-LF, while its faint-end is steeper than both the Fiore et al. (2012) and Fontanot et al. (2007) estimates, but still in the range allowed by the Shankar & Mathur (2007) analysis.

In order to compute the QSO contribution to reionization, we compute the rate of emitted ionizing photons per unit comoving volume Γ_{AGN} as a function of redshift, following the same formalism as in Shankar & Mathur (2007, see also Madau et al. 1999):

$$\Gamma_{AGN}(z)[s^{-1}Mpc^{-3}] = \int_{\nu_H}^{\nu_{up}} \sigma_{\nu} \frac{\rho_{\nu}(z)}{h_p \nu} d\nu \quad (1)$$

$$\rho_{\nu}(z)[erg s^{-1}Hz^{-1}Mpc^{-3}] = \int_{L_{min}}^{\infty} \Phi(L, z) L_{\nu}(L) dL \quad (2)$$

In the above equations, L_{ν} is in $erg s^{-1} Hz^{-1}$, h_p represents the Planck’s constant, $\nu_H = 3.2 \times 10^{15}$ Hz is the frequency at the Lyman Limit (i.e. 912 Å); $\nu_{up} = 12.8 \times 10^{15}$ Hz is the usual upper limit to the integration, since photons more energetic are preferentially absorbed by He atoms. In practice, we assume that the absorbing cross section for neutral hydrogen σ_{ν} is unity between ν_H and ν_{up} , and zero outside this range. This crude approximation gives us a good grasp of the maximum contribution of QSO to the reionization background. We also assume that all the ionizing photons associated with the AGN spectra contribute to the ionizing background (i.e. $f_{esc} = 1$). In the calculations, we assume a QSO spectral continuum of the form $f_{\nu} = \nu^{\gamma}$ and we assume a slope $\gamma = -1.76$ blueward of the Ly_{α} line (Telfer et al. 2002). In the following, we will compare Γ_{AGN} with the required total ionizing photon rate per unit comoving volume Γ_{ion} , using the formalism proposed in Madau et al. (1999), rescaled to WMAP7 cosmology as in (Pawlik et al. 2009):

$$\Gamma_{ion}(z)[s^{-1}Mpc^{-3}] = 0.027 \kappa \left(\frac{C}{30}\right) \left(\frac{1+z}{7}\right)^3 \left(\frac{\Omega_b h_{70}^2}{0.0465}\right)^2 \quad (3)$$

where we convert the critical star formation rate into a photon rate, by assuming that $\kappa = 10^{53.1} s^{-1}$ LyC photons per $M_{\odot} yr^{-1}$ are produced (see e.g. Shull et al. 2012, see also eq. 6 below) and C refers to the clumping factor of the intergalactic medium. Early work (see e.g. Madau et al. 1999; Shankar & Mathur 2007) assumed a high value $C = 30$ for the clumping factor, following the results of numerical simulations by Gnedin & Ostriker (1997), and concluding that the space density of ionizing photons deducted by observations was in most cases insufficient to reionize the Universe and/or kept it ionized. More recent theoretical estimates (see e.g. Bolton & Haehnelt 2007; Pawlik et al. 2009; Haardt & Madau 2012 revised the value of the clumping factor towards lower values. In particular, Pawlik et al. (2009) estimates $C = 6$ as adequate for gas with densities of the order of the critical density for the onset of star formation, while finding an even lower $C = 3$ value for gas with overdensities ~ 100 . It is also worth stressing that C is expected to be a decreasing function of redshift. For example Haardt & Madau (2012) propose the following fitting formula:

$$C(z) = 1 + 43 \times z^{-1.71} \quad (4)$$

derived for gas with overdensities ~ 100 . Eq. 4 is fully consistent with the Pawlik et al. (2009) estimate on the same overdensity scale. Lower values for the clumping factor reduce considerably the number of ionizing photons required to keep the Universe ionized at $z > 6$, mitigating the requests on the observed astrophysi-

cal sources. In the following, we will assume a redshift dependent clumping factor as in eq. 4.

2.2 High- z LBGs Luminosity Functions

In order to estimate the number of ionizing photons produced by the galaxy population, we consider the high- z luminosity function of Lyman Break Galaxies (LBGs hereafter) as estimated by Bouwens et al. (2011). Following these authors we describe the LBG-LF in the redshift range $3.5 \lesssim z \lesssim 8$ as an evolving Schechter function (i.e. whose parameters are evolving with cosmic time, see table 1 in Bouwens et al. 2011). We then compute the luminosity density ρ_{UV} using eq. 2 and we convert it to an estimate of the star formation rate density (ρ_{SFR}) using the Haardt & Madau (2012) conversion factor:

$$\rho_{\text{SFR}}(z) [\text{M}_{\odot} \text{yr}^{-1} \text{Mpc}^{-3}] = \frac{\rho_{\text{UV}}(z) [\text{erg s}^{-1} \text{Hz}^{-1} \text{Mpc}^{-3}]}{1.05 \times 10^{28}} \quad (5)$$

Major uncertainties affect the conversion between UV luminosity density and the ρ_{SFR} . First of all, UV observations are severely affected by dust attenuation. Bouwens et al. (2007) estimated that $z > 4$ LBGs suffer lower attenuation levels than lower- z counterparts, and they suggest that the ρ_{SFR} obtained from eq. 5 may be underestimated by a factor ~ 1.5 . Moreover, the conversion factor itself critically depends on the details of the Stellar Population Synthesis modeling; in particular the chosen Initial Stellar Mass Function play a relevant role, by determining the relative abundance of massive stars, the main contributors to UV fluxes. The value we use in eq. 5 has been computed assuming a Salpeter IMF. If we consider, i.e. a Kroupa IMF, its value is reduced by a factor ~ 1.5 . In the following, we take into account all these sources of uncertainties by assuming eq. 5 as a good representation of the mean conversion and by defining a “maximal” and a “minimal” model by increasing and decreasing the resulting ρ_{SFR} by a factor 1.5, respectively. We then estimate the rate of ionizing photon production using the conversion factor proposed for a low-metallicity gas by Shull et al. (2012, see also Madau et al. 1999):

$$\Gamma_{\text{LBG}}(z) [\text{s}^{-1} \text{Mpc}^{-3}] = \kappa f_{\text{esc}} \rho_{\text{SFR}}(z) \quad (6)$$

where f_{esc} represents the escape fraction², i.e. the fraction of produced ionizing photons which are able to escape the local environment and ionize the intergalactic medium. This parameter has a key importance in order to evaluate the contribution of LBGs to the ionizing background, but its very poor constrained. At $z \sim 3 - 4$, proposed values range from low ($f_{\text{esc}} < 5\%$, Vanzella et al. 2010b), to relatively high values ($f_{\text{esc}} \gtrsim 20\%$, Shapley et al. 2006; Iwata et al. 2009).

3 DISCUSSION

3.1 The AGN contribution to the ionizing background

First of all we consider the AGN contribution to the ionizing background. At variance with previous analyses we don't fix L_{min} in

² Most observational works focus on the *relative* escape fraction, i.e. the fraction of escaping LyC photons, relative to the fraction of escaping non-ionizing ultraviolet photons. Since the relative f_{esc} takes into account the dust attenuation, it is then possible to convert between the two determinations. For the purposes of this work we just deal with the absolute f_{esc} .

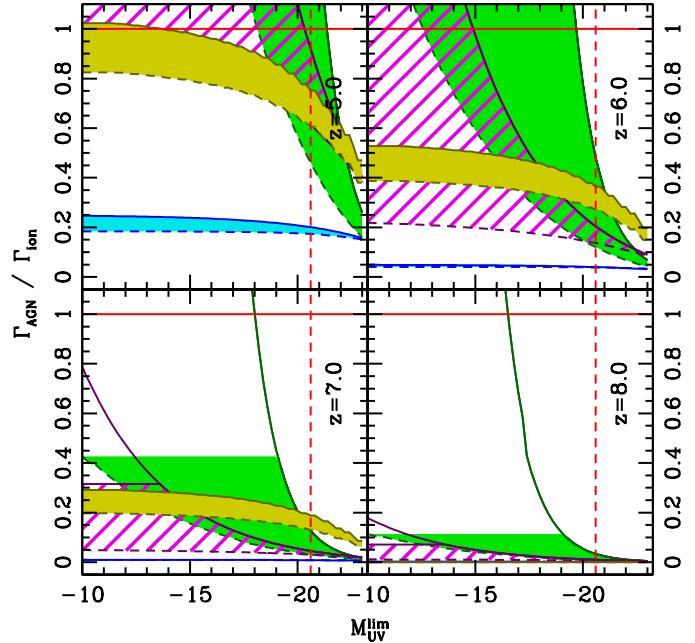


Figure 2. Estimated AGN contribution to reionization at different cosmic epochs. Lines and colours as in Fig. 1. Shaded areas represent allowed contributions after Helium reionization has been taken into account (see text for more details). Dashed vertical lines represent the actual limit ($M_{\text{UV}} \sim -20.6$) of faint QSO searches as defined in Shankar & Mathur (2007).

eq. 2, but we study how the ratio $\Gamma_{\text{AGN}}/\Gamma_{\text{ion}}$ evolves as a function of redshift and limiting magnitude. We also compute the AGN contribution to the reionization by applying the same approach to our GSMF-derived AGN-LF (sec. 2.1), and include these results in Fig. 2 (red lines and red hatched area). Following the same (a) to (f) prescriptions described in sec. 2.1, we estimate that the putative AGN luminosity associated to a Jeans Mass of pristine gas³ is roughly $M_{\text{UV}} \sim -10$. The formation of the ancestors of SMBHs at very high redshifts has been discussed by a number of authors (see e.g. Petri et al. 2012 and references therein), showing that both heavy ($> 10^5 M_{\odot}$) and light SMBHs seeds are physically plausible at the same scales accessible for gas cooling and star formation. We further assume that all ionizing photons associated with the AGN spectra are available for ionizing the IGM and we show our results in Fig. 2.

We find that the QSO contribution at the current observational limit ($M_{\text{UV}} \sim -20.6$), is not negligible at $z \sim 6$, but still insufficient to provide the required rate of ionizing photons. The difference with respect to analogous works in the literature (e.g. Shankar & Mathur 2007), is to be ascribed to the lower clumpiness adopted here.

At higher redshift the contribution of AGNs to the ionizing background decreases rapidly, becoming of the order of a few percent at $z \sim 8$ and negligible thereafter. To obtain a relevant AGN contribution (i.e. $> 10\%$) at these redshifts a steep faint end is re-

³ The limiting mass M_J for the collapse of a cloud of cold gas into stars is usually determined by comparing its thermal and gravitational energy; by assuming typical values for the temperature and density we obtain $M_J \sim 10^5 M_{\odot}$.

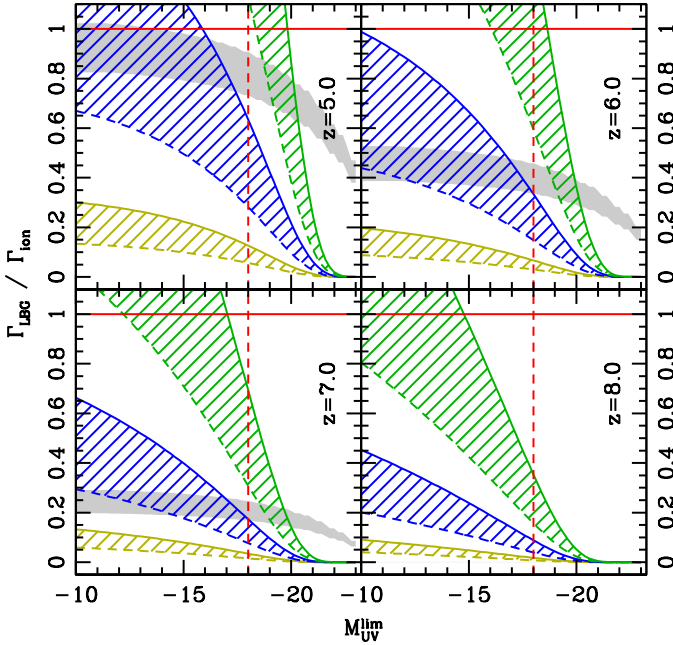


Figure 3. Estimated LBG contribution to reionization at different cosmic epochs. Yellow, blue and green lines and hatched regions refer to the integrated contribution of LBGs for $f_{\text{esc}} = 1\%$; 5% ; 20% respectively. Solid and dashed line refer to the “maximal” and “minimal” models (see text for more details). The grey shaded area corresponds to the estimated AGN contribution from the Fiore et al. (2012) high- z AGN-LF shown in Fig. 2. Dashed vertical lines represent the actual limit ($M_{\text{UV}} \sim -18$) of faint LBG searches as defined in Bouwens et al. (2011).

quired for the high- z AGN LF (steeper than the GSMF faint-end slope determined by Santini et al. (2012)) and an integration to very low luminosity limits, under the hypothesis that very faint AGNs are characterized by the same properties of their bright counterparts. Another possibility is that the evolution of the low-luminosity AGN population becomes slower with respect to the $3 < z < 5$ estimates.

We have also imposed that our analysis be consistent with present constraints on the HeII reionization (see e.g. Furlanetto & Oh 2008), i.e. areas of the parameter space predicting too many photons with energies larger than 4 Ryd and therefore producing HeII reionization at redshifts $z \gtrsim 5$ are forbidden. To this end we assume the same clumping factor as adopted for Hydrogen reionization, a ratio between the number densities of Helium and Hydrogen atoms equal to $Y/4(1-Y)$ (where $Y = 0.258$ represents the cosmic fraction of Helium by mass), a recombination rate for Helium 6 times faster than for Hydrogen and we integrate our standard QSO spectral shape between 4 and 16 Ryd. Shaded areas in fig. 2 thus represents the allowed contribution to the ionizing background according to this analysis.

3.2 The LBG contribution to the ionizing background

In Fig. 3 we present the estimated contribution of LBGs to cosmic reionization for different f_{esc} values. Also for this class of sources we integrate the contribution of sources down to $M_{\text{UV}} \sim -10$. We directly compare these results with the contribution from the AGN-LF, and in particular with the results of Fiore et al. (2012, grey shaded area). We confirm the result of Pawlik et al. (2009) that

observed LBGs may account for the total required ionizing photon budget at $z \sim 6$ if $f_{\text{esc}} \sim 20\%$; at higher redshifts, we have to integrate the LBG-LF to increasingly fainter limiting magnitudes (up to $M_{\text{UV}} \sim -10$ at $z \sim 9$), in order to produce enough ionizing photon to fully account for cosmic reionization. However, if $f_{\text{esc}} \sim 5\%$ for the whole LBG population, the LBG contribution is not enough to account for the whole required ionizing photon rate at $z \gtrsim 7$, even if we extrapolate the LBG-LF up to the fainter magnitudes, and it becomes roughly compatible with that of AGNs for $z \lesssim 7$. In order to achieve high- z reionization with LBGs only, a substantial contribution to the ionizing background of sources fainter than the actual observational limit is required and/or a very different (i.e. increasing) f_{esc} with respect to their bright counterparts.

In order to test this hypothesis we impose a simple luminosity-dependent f_{esc} scenario to our maximal model by defining $f_{\text{esc}} = 0$ for $M_{\text{UV}} < -18.00$ and a linearly increasing f_{esc} with increasing magnitude:

$$f_{\text{esc}} = \min[1, \eta \times (M_{\text{UV}} + 18.00)] \quad (7)$$

Despite the lack of constraints on the distribution of f_{esc} in different galaxy population, this exercise allows us to provide a qualitative estimate for the typical magnitude of objects responsible for the bulk of reionization and their expected escape fractions, if f_{esc} is indeed a decreasing function of luminosity. This simple toy model predicts that complete reionization at $z = 8$ by LBGs alone is achieved at typical magnitudes $M_{\text{UV}} \sim -13.5, -15, -15.5$ for $\eta = 0.1, 0.2, 0.3$ respectively. The predicted corresponding escape fractions are $f_{\text{esc}} 50, 60, 80\%$. A similar result is obtained at $z = 9$ (typical magnitudes $M_{\text{UV}} \sim -12.5, -14, -15$ and $f_{\text{esc}} \sim 55, 75, 90\%$). This results are compatible with the recent hydrodynamical simulations (see e.g., Ciardi et al. 2011), which require rather high f_{esc} values for fainter LBGs. It is also worth noting that, in general, lower f_{esc} values are still compatible with an LBG-driven reionization if a redshift increasing efficiency of ionizing photons production and/or a top-heavy IMF are assumed (see e.g. Schneider et al. 2002).

3.3 Combined AGN-LBG contribution to ionizing background

Fig. 4 shows the combined AGN+LBG contribution to the reionization of the Universe. For the sake of simplicity we only consider the maximum AGN contribution as estimated on the basis of the AGN-LF of Fiore et al. (2012, marked as a solid line in each panel): this is at the same time a conservative but representative choice among the various LF estimates that we consider in sec. 2.1. From a comparison with the results shown in Fig. 3 it is apparent that AGNs may significantly help reducing the gap between the LBG ionizing photon production rate and the required amount of ionizing photons up to $z \sim 7$. For a given f_{esc} the minimum luminosity of the galaxies required to match the theoretically estimated ionization limit is significantly increased. Nonetheless, at the highest redshift considered, it is still not possible to reach the expected space density of ionizing photons for reionization if $f_{\text{esc}} \sim 5\%$. Again, in order to reionize the Universe with LBGs and AGNs combined at such high redshifts, either f_{esc} has to be higher than the current estimates (at least for the faint LBG population, which is assumed to provide the largest contribution), and/or the evolution of the LF has to slow down with respect to the present estimates. In Fig. 5, we then show the $\Gamma_{\text{AGN}}/\Gamma_{\text{LBG}}$ ratio as a function of M_{UV} and redshift. For the AGN population we consider as representative the

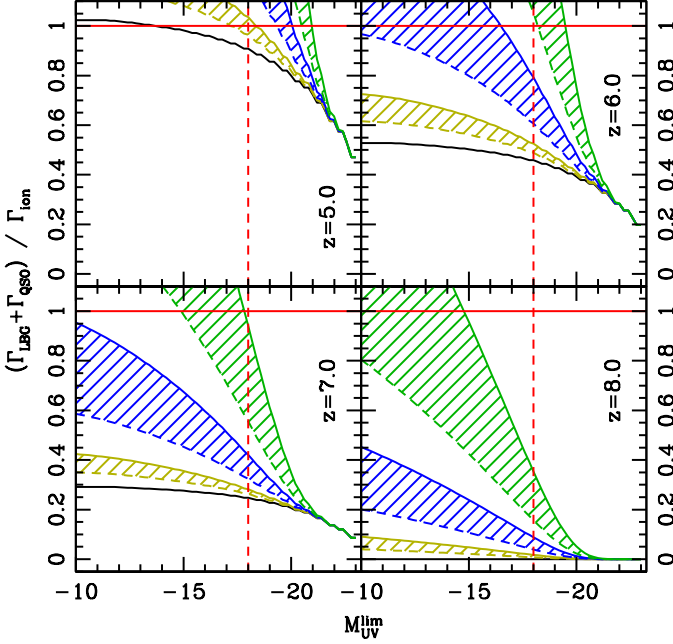


Figure 4. Combined LBG and AGN contributions to reionization. Colours and lines as in Fig. 3. In each panel we consider the maximal AGN contribution from the high- z AGN-LF from Fiore et al. (2012, marked by the solid line in each panel, see text for more details).

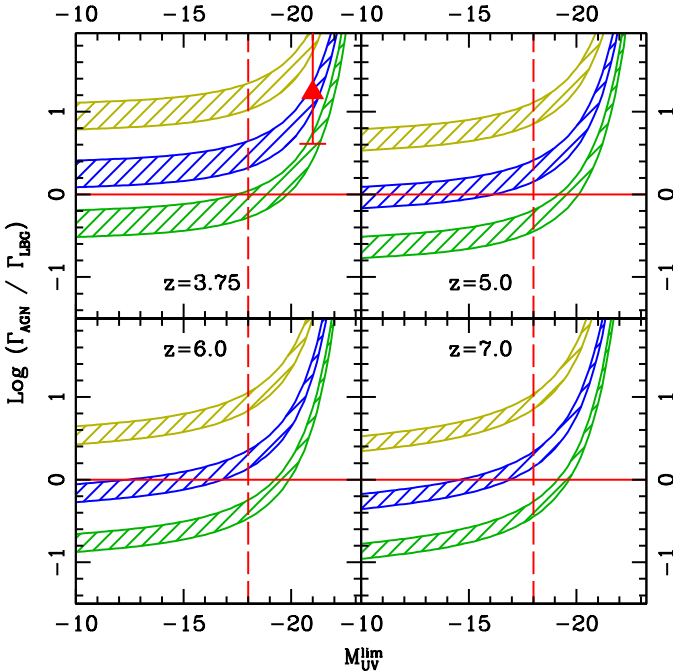


Figure 5. Logarithmic ratio between the AGN and LBG contributions to the reionization. As a reference for AGNs, the Fiore et al. (2012) AGN-LF has been considered. Colours and lines as in Fig. 3. The red filled triangle marks the position of our measurement at $3.4 < z < 4.0$ carried out in the GOODS fields (see text for more details).

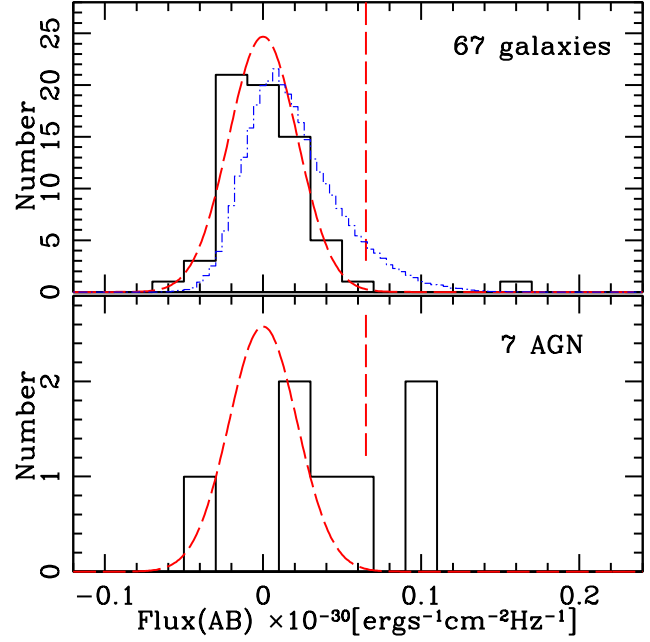


Figure 6. Distribution of U-band fluxes (probing the rest-frame LyC) for 67 LBGs (upper panel) and 7 AGNs (lower panel) in the GOODS South field (selected with $3.4 < z < 4$ and $23.5 < i_{775} < 26$). Fluxes have been measured in both cases within an aperture of $1.2''$ diameter. The red dashed Gaussian distributions show the expected distribution of null detections normalized to the total number of measurements in each panel. For comparison, the dot-dashed blue histogram shows the expected distribution of fluxes for galaxies with an $f_{\text{esc}} = 10\%$ (the IGM absorption being simulated as in Vanzella et al. 2010b). The vertical dashed line marks the 3σ confidence limit.

Fiore et al. (2012) LF, while for the LBG population we show results for $f_{\text{esc}} = 1\%, 5\%$ and 20% . From Fig. 5 is clear that Γ_{AGN} is decreasing at increasing redshifts at a faster pace relative to Γ_{LBG} independently on f_{esc} . The latter contribution becomes dominant for faint sources at $z > 5$ for $f_{\text{esc}} \gtrsim 5\%$.

An interesting reference point can be obtained by studying the LBGs and AGNs in the GOODS South field, selected in equal redshift and magnitude intervals, $3.4 < z < 4$ and $23.5 < i_{775} < 26$. Following the procedure described in Vanzella et al. (2010b), we have measured the flux of 67 LBGs and 7 AGN in the U-band (probing the rest-frame LyC) using a circular aperture of $1.2''$ diameter. As shown in Fig. 6, one galaxy (dubbed *Ion1* in Vanzella et al. (2012)) and two AGNs are detected above the 3σ confidence level. The average flux from AGN turns out to be $(0.041 \pm 0.08) \times 10^{-30} \text{ erg}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$. In order to compute the corresponding quantity for galaxies we have considered that the distribution of their UV fluxes is characterized by 66 non-detections and one outlier. We have therefore assumed as an average UV flux of galaxies the flux of the outlier divided by 67 (we would obtain a similar value by averaging over the whole distribution) and as 1σ confidence levels those computed by Gehrels (1986) for small numbers of events (in this case one), obtaining $(0.0024^{+0.0055}_{-0.0020}) \times 10^{-30} \text{ erg}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$. The statistics are poor but allow us to roughly estimate a ratio between the AGN and LBG contribution to the UV ionizing background (shown in Fig. 5 with a red triangle) of 17^{+105}_{-13} . This value is conveniently independent on the IGM transmission and is

consistent with the $\lesssim 5\%$ estimate of the f_{esc} from galaxies discussed in Vanzella et al. (2010b).

It is worth noting that a similar measurement and result has been obtained at lower redshift by Cowie et al. (2009). These authors study the ionizing fluxes associated with the AGN and galaxy populations at $z \sim 1.15$ in the GOODS-North field by means of observations with the Galaxy Evolution Explorer (GALEX). Their results show the presence of a detectable signal corresponding to known AGNs/QSOs, while stacking analysis of galaxy images provides no evidence for a significant ionizing flux (compatible with $f_{\text{esc}} \lesssim 1\%$).

4 CONCLUSIONS

We have critically discussed in view of recent results the contribution to cosmic reionization at $z > 5$ of both high- z QSOs (Fontanot et al. 2007; Shankar & Mathur 2007; Fiore et al. 2012) and LBGs (Bouwens et al. 2011). In order to take into account the contribution from AGN fainter than the current observational depths we have also used a derivation of the AGN LF based on the evolution of the galaxy stellar mass function (Santini et al. 2012). In the following we assume $z \sim 7$ (e.g. Mitra et al. 2012) as the fiducial redshift for a rapid transition of the hydrogen from a significantly neutral condition to a neutral fraction $x_{\text{HI}} \ll 10^{-3}$.

Our results show that

(i) In order to achieve the HI reionization at $z \sim 7$ the properties of the AGN population have to be pushed to rather extreme values in terms of steepness of the faint end of the LF ($\alpha \lesssim -2$) and contribution of very faint (up to $M_{UV} \sim -10$) objects. But in the case such conditions were met we would expect the reionization of HeII to take place, owing to the typical AGN SED, above redshift $z \sim 5$, which is in contrast with present observations (e.g. Fechner et al. (2006); Zheng et al. (2008)). AGN alone, at least in their standard manifestation, cannot be responsible for the reionization of HI.

(ii) The LBG population may account for the whole photon budget needed for reionization, but only if the mean escape fraction of this population is of the order of $f_{\text{esc}} \sim 20\%$ and very faint dwarf galaxies provide a substantial contribution. Despite such an high f_{esc} is still compatible with observational constraints (Shapley et al. 2006; Iwata et al. 2009), several evidences point out that these values are not typical for the whole high- z LBG population (Vanzella et al. 2010b, see e.g.). If mean f_{esc} values are indeed of the order of 5%, and more similar to $z \sim 1$ results (Cowie et al. 2009), the contribution of LBGs alone is not enough to account for cosmic reionization at $z \gtrsim 7$, and we are forced either to advocate additional ionizing sources or a strong redshift/luminosity evolution of f_{esc} .

(iii) If $f_{\text{esc}} \sim 5\%$, the AGN population can provide a significant contribution to the total photon budget and help achieving reionization not earlier than $z \sim 7$.

(iv) If $f_{\text{esc}} \lesssim 5\%$ for the brighter ($L \gtrsim L_*$) LBG galaxies a viable solution is to advocate an increasing f_{esc} with decreasing luminosity, as it may be expected if shallower potential wells are more easily cleared of (neutral) hydrogen gas (see e.g. Mori et al. 2002; Yajima et al. 2011). A simple toy model with a linear growth of f_{esc} with increasing magnitude shows that, in the case of a negligible contribution to the ionizing rate from brighter LBGs, we need to assume f_{esc} of the order of 70% for sources fainter than the present observational limits to provide a substantial contribution to reionization. These results are fully consistent with the recent findings of Kuhlen & Faucher-Giguere (2012): these authors use a different

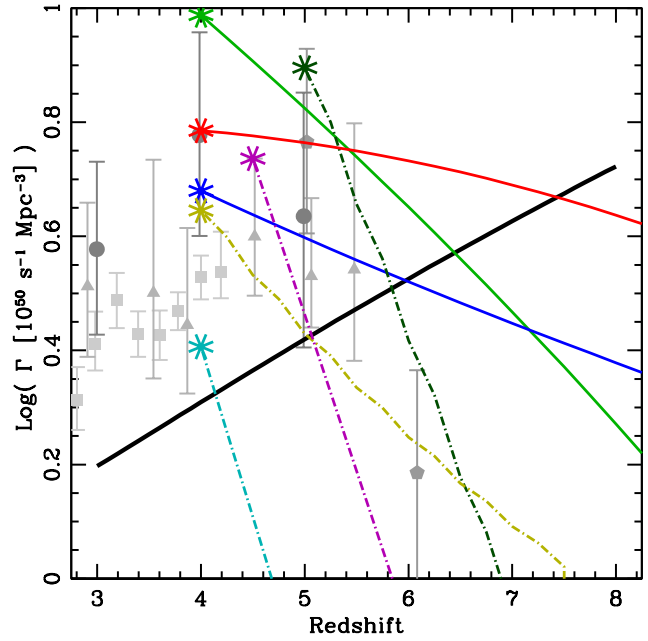


Figure 7. Comparison between observed and required ionizing background. Observed data from Bolton & Haehnelt (2007, circles), Becker et al. (2007, triangles), Faucher-Giguère et al. (2008, squares), Calverley et al. (2011, pentagons). The black solid line mark the assumed minimum rate of emitted ionizing photons per unit comoving volume for Universe ionization. The cyan asterisk and dot-dashed line refers to the level corresponding to the maximum contribution from the Fontanot et al. (2007) QSO-LF, integrated up to $M_{\text{lim}} = -10$; the yellow asterisk and dot-dashed line to the maximum contribution from the Fiore et al. (2012) QSO-LF, integrated up to $M_{\text{lim}} = -10$; the dark green asterisk and dot-dashed line to maximum contribution from the Shankar & Mathur (2007) QSO-LF, integrated up to $M_{\text{lim}} = -20$; the dark green asterisk and dot-dashed line to maximum contribution from the GSMF-derived AGN-LF, integrated up to $M_{\text{lim}} = -20$; the blue asterisk and solid line to maximum contribution from the Bouwens et al. (2011) LBG-LF, integrated up to $M_{\text{lim}} = -10$ assuming $f_{\text{esc}} = 5\%$; the green asterisk and solid line to maximum contribution from the LBG-LF, integrated up to $M_{\text{lim}} = -18$ assuming $f_{\text{esc}} = 20\%$; the red asterisk and solid line to the luminosity-dependent f_{esc} scenario ($\eta = 0.1$) integrated up to $M_{\text{lim}} = -14$. The different slope for the two LBG-LF based models are due to the redshift dependent evolution of the LF shape, as modeled by Bouwens et al. (2011) results.

approach to compute the contribution of LBGs to the ionizing photons, based on the comparison of the LBG-LF with the expected Thompson optical depth and observational constraints on the Ly α forest, favouring a scenario where f_{esc} increases from $z = 4$ to $z = 9$.

In Fig. 7 we compare our empirical predictions with the present observational constraints on the measured ionizing background. We consider photoionization rate data derived from the observed Ly α -forest effective opacity (Bolton & Haehnelt 2007; Becker et al. 2007; Faucher-Giguère et al. 2008) and from the QSO proximity effect (Calverley et al. 2011) and convert them into ionizing photons per unit comoving volume (Γ_{BKG}), following the same procedure and assumptions as in Kuhlen & Faucher-Giguere (2012, their eq. 12), and using the mean free path of ionizing photons as measured by Prochaska et al. (2009). The assumed minimum rate of emitted ionizing photons per unit comoving volume for Universe ionization below redshift 5 is only about a factor 2-

3 below the measured UV background. In this way, if the sources responsible for reionization at $z \sim 7$ have a rapid density evolution, they would quickly exceed the constraint of the measured UV background.

Fig. 7 shows that the space density evolution of AGNs (as estimated by Fontanot et al. 2007; Shankar & Mathur 2007; Fiore et al. 2012) is too strong for these objects to provide a significant contribution to reionization at $z \gtrsim 7$; LBGs show a milder density evolution for faint M_{lim} values, steepening as f_{esc} increases (and M_{lim} brightens), the steepening being due to the redshift dependent evolution of the LF shape (Bouwens et al. 2011).

In both cases our empirical models do not predict enough ionizing photons at $z > 7$, if we force them to obey the constraints on Γ_{BKG} and f_{esc} is kept constant. Also in this case, the most likely solution for an LBG-driven early reionization requires an increase of f_{esc} either with decreasing luminosity (or with increasing redshift): this is clearly shown by the red line in fig. 7, which represents the contribution to the ionizing background in the luminosity-dependent f_{esc} scenario (eq. 7, $\eta = 0.1$).

The exact relative contributions from AGNs and LBGs critically depends on the details of the slopes of the corresponding faint-end LFs, on the faintest luminosity limits of these populations and on f_{esc} . Given the present uncertainties in its determination, better constraints on the high- z AGN-LF faint-end slope would be of fundamental importance to understand the maximal contribution of the AGN population to the ionizing background. In general, our analysis suggests that pushing the actual observational limits at least one magnitude fainter, despite very demanding from the observational side, would be quite rewarding to clearly understand the relative importance of different astrophysical sources in determining the ionization state of the early Universe.

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